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Towards a complete census of high- z ULIRGs with *Herschel*

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Abstract. Using *Herschel* PACS and SPIRE observations as part of the HerMES project, we explore the far-IR properties of a sample of mid-IR selected starburst dominated ultra-luminous infrared galaxies (ULIRGs) at $z \sim 2$. We derive robust estimates of infrared luminosities (L_{IR}) and dust temperatures (T_{d}) of the population and find that galaxies in our sample range from those that are as cold as high- z sub-millimeter galaxies (SMGs) to those that are as warm as optically faint radio galaxies (OFRGs) and local ULIRGs. We also demonstrate that a significant fraction of our sample would be missed from ground based (sub)mm surveys (850-1200 μm) showing that the latter introduce a bias towards the detection of colder sources. Similarly, based on PACS data as part of the PEP project, we construct for the first time the full average SED of a sub-sample of infrared luminous Lyman break galaxies at $z \sim 3$, and find them to have higher T_{d} when compared to that of SMGs with comparable L_{IR} . We conclude that high- z ULIRGs span a wide range of dust temperatures, larger than that seen in local ULIRGs, and that *Herschel* data provide the means to characterize the bulk of the ULIRG population, free from selection biases introduced by ground based (sub)mm surveys.

1. Introduction

A key parameter to study galaxy evolution is to probe the census of the star formation activity, both in the distant and local universe. To this direction, it has been shown that the contribution of luminous infrared galaxies ($L_{\text{IR}} > 10^{11} L_{\odot}$) to the star formation density is progressively rising as we look back in the cosmic time, at least up to $z \sim 2$. Indeed, although they were found to be rare in the local universe and to account only for $\sim 5\%$ of the total infrared energy emitted by galaxies at $z \sim 0$, LIRGs along with the ULIRGs ($L_{\text{IR}} > 10^{12} L_{\odot}$), dominate the SFR density at $z \sim 1-2$, accounting for the 70% of the star formation activity at these epochs (e.g. Le Floc'h et al. 2005).

Until recently, the most successful methods for selecting high- z ULIRGs was their direct far-IR detection via ground based (sub)millimeter surveys (e.g. Hughes et al. 1996). However, the submillimetre technique introduces a bias towards the selection of ULIRGs with lower dust temperatures while it misses warmer ULIRGs. First observational evidence of a missing population of high- z dusty star-forming galaxies with hotter dust was been given by Chapman et al. (2004) using a selection of radio-detected but sub-mm-faint galaxies (OFRGs) with UV spectra consistent with high- z starbursts. Recent studies (Magnelli et al. 2010 and Chapman et al. 2010) have shown that there is no overlap between the two populations (SMGs and OFRGs) in the $L_{\text{IR}} - T_{\text{d}}$ space, leaving a large gap between them. In other words, it appears that if SMGs are biased towards the colder high- z ULIRGs, then OFRGs trace only the ULIRGs with warmest

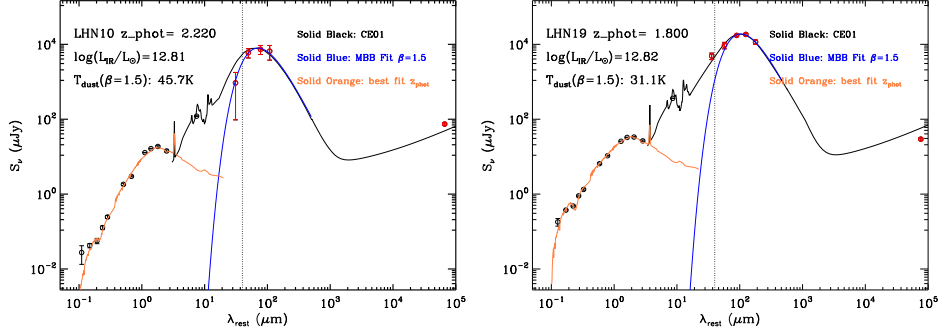


Figure 1. Rest-frame SEDs and derivation of the far-IR properties for two ULIRGs in our sample. Solid orange line shows the best fit template up to observed $8\mu\text{m}$ as derived by LEPHARE photo- z code. Solid black line shows the best fit CE01 model while the blue line depicts the best-fit modified black body (with $\beta=1.5$), used to derive T_d estimates. The vertical dotted line indicates the wavelength cut, below which photometric data were not considered in the modified black body fit. Red circles denote it Herschel data

T_d . These suggest that in order to obtain the complete census of high- z ULIRGs, a selection independent of the sub-mm emission should be employed.

Another technique that has been proven to pick high- z starburst dominated ULIRGs efficiently, is based on mid-IR color selection, fine tuned to probe the rest-frame $1.6\mu\text{m}$ bump, prominent in the SED of star-forming galaxies. Among others (e.g. Farrah et al. 2003), Huang et al. (2009) demonstrated that a simple IRAC color criteria: $0.05 < [3.6] - [4.5] < 0.4$ and $0.7 < [3.6] - [8.0] < 0.5$, coupled with a S_{24} flux cut ($S_{24} > 0.2\text{mJy}$), selects star-burst dominated ULIRGs in a narrow redshift range of $1.5 < z < 2.5$. Using Herschel PACS and SPIRE data, as part of the HerMES (Oliver et al. 2011 in prep) project we explore the far-IR properties of the population, derive robust T_d and L_{IR} measurements for the bulk of the population and compare our sample to that of other high- z ULIRGs. All results, figures and discussions here, are presented in detail in Magdis et al. (2010a,b).

2. Far-IR properties of IRAC selected ULIRGs

We select sources with $0.05 < [3.6] - [4.5] < 0.4$, $-0.7 < [3.6] - [8.0] < 0.5$, and $S_{24} > 0.2\text{mJy}$ in Lockman Hole and GOODS-N, and with at least two detections in the either of PACS and SPIRE bands. Our sample consist of 25 ULIRGs with a median $z = 2.01$ and with 18 out of 25 objects lying in narrow redshift range ($1.7 < z < 2.3$) (for details see Magdis et al. 2010a). To derive estimates for the L_{IR} of the galaxies in our sample, we first convert their SED to rest-frame applying k-corrections and then fit the PACS and SPIRE data with the libraries of Chary & Elbaz (2001) (CE01) and Dale & Helou (2002). Results based on the two methods are in very close agreement indicating a median $L_{\text{IR}} = 3 \times 10^{12} L_{\odot}$. To derive the dust temperature of galaxies in our sample, we use a single temperature modified black body fitting form. This model was fit to *Herschel* data with rest-frame $> 40\mu\text{m}$, assuming a fixed emissivity index of $\beta=1.5$. Two examples of the restframe SEDs along with the best-fit CE01 templates for two ULIRGs in our sample are shown in Figure 1. We find that our sample spans in

wide range of dust temperatures $25 < T_d < 62$ (K), while the luminosities vary by less than an order of magnitude $12.24 < \log(L_{\text{IR}}/L_\odot) < 12.94$. The median values are $T_d = 42.3$ K, and $L_{\text{IR}} = 3 \times 10^{12} L_\odot$.

3. *Herschel* reveals a T_d unbiased selection of $z \sim 2$ ULIRGs

We now compare the far-IR properties of our sample with that of local and high- z ULIRGs selected by different techniques. We consider the large set of $z \sim 2$ SMGs (Chapman et al. 2005 and Kovacs et al. 2006), a sample of $z \sim 2$ OFRGs (Casey et al. 2009, Magnelli et al. 2010) and a compilation of local/intermediate- z ($0 < z < 0.98$) ULIRGs (Clements et al. 2010, Farrah et al. 2003 and Yang et al. 2007). In all these studies, the method to derive T_d estimates is similar to ours, fitting modified black-body models to the far-IR photometric points and assuming $\beta = 1.5$. This comparison is illustrated in Figure 2(top).

Our observations confirm the existence of ULIRGs in the high- z universe with dust temperature higher than that of SMGs. Furthermore, it seems that the selection of high- z ULIRGs based on the detection of the $1.6\mu\text{m}$ bump does not favour a particular T_d , selecting ULIRGs that overlap with the SMGs and OFRGs but also ULIRGs of intermediate T_d . Indeed, for the luminosity bin of our sample, SMGs have a median $T_d = 36 \pm 8$ K while OFRGs are considerably warmer with median $T_d = 47 \pm 3$ K (Magnelli et al. 2010) while galaxies in our sample range from those that are as cold as SMGs to objects as warm as OFRGs, with a significant fraction located in the intermediate region between the two samples, bridging the two populations. We also note that a large fraction of the sample falls in the $T_d - L_{\text{IR}}$ relation of the local ULIRGs. Finally, our data indicate that the T_d dispersion of high- z ULIRGs is larger than that of the local ULIRGs as derived based on IRAS/AKARI observations. A similar conclusion is reached by Hwang et al. (2010).

We also estimate the S_{850} flux densities of our sample based on the best fit CE01 model. The predicted S_{850} fluxes of our sample along with the measured sub-mm flux of high- z SMGs are plotted versus the derived T_d of the two populations in Figure 2 (bottom). We also overplot tracks in constant L_{IR} . This plot illustrates that a significant fraction (60%) of the mid-IR selected ULIRGs in our sample have S_{850} flux densities lower than that of the SMGs, lie below the confusion limit at $850\mu\text{m}$ (2-3 mJy) and hence would be missed by ground-based (sub)mm surveys. Nevertheless, we also find IRAC-peakers with predicted S_{850} above the detection limit and which therefore should be detected in the sub-mm. Observational data confirm our results, with $\sim 40\%$ of the sample being detected in the submm bands (e.g. Lonsdale et al. 2009). We conclude that our analysis strongly suggests that *Herschel* data allow us for the first time to characterize the far-IR properties of 50% of the mid-IR selected ULIRGs that would be missed by ground based (sub)mm surveys and reveal that their properties are different from that of SCUBA/IRAM selected galaxies.

4. T_d of LBGs at $z \sim 3$

Similar results were reached, when we considered, a sub-sample of $24\mu\text{m}$ detected Lyman break galaxies at $z \sim 3$ (MIPS LBGs). Using PACS data as part of the PEP project, we derived a median IR luminosity of $L_{\text{IR}} = 1.6 \times 10^{12} L_\odot$, placing these

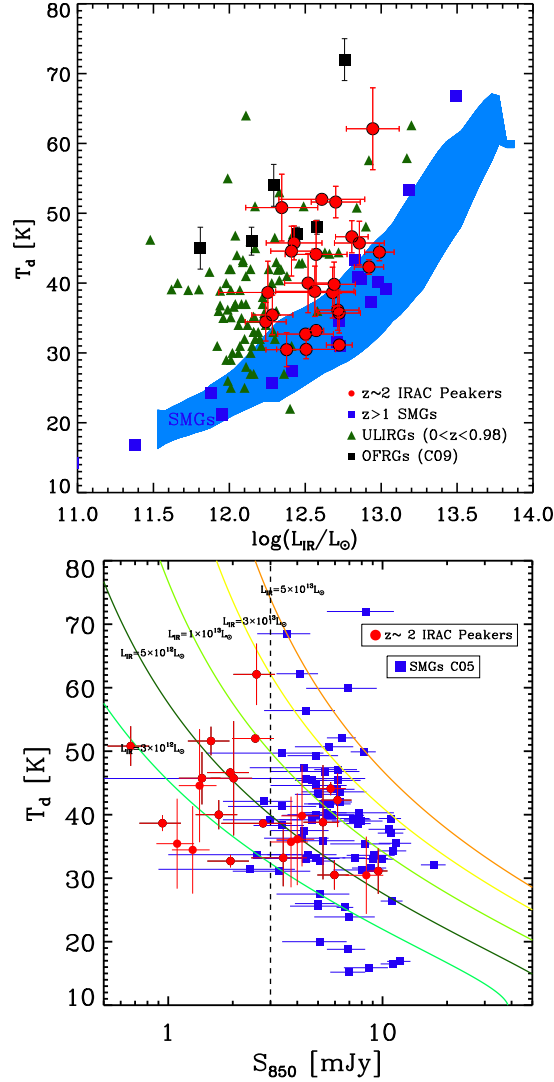


Figure 2. top) The $L_{\text{IR}} - T_d$ relation for IRAC selected ULIRGs (red circles). Included are results for local/intermediate- z ULIRGs (green filled triangles, Farrah et al. 2003, Clements et al. 2010, Yang et al. 2007), high- z SMGs (blue squares, Chapman et al. 2005, Kovacs et al. 2006) and OFRGs (black squares, Casey et al. 2009). The cyan shaded area denotes the 2σ envelope of the $L_{\text{IR}} - T_d$ relation of high- z SMGs. For a given L_{IR} , our sample span in a wide range of dust temperatures, bridging the “cold” high- z SMGs to the “warmer” local/intermediate- z ULIRGs and ~ 2 OFRGs. bottom) T_d versus the estimated S_{850} flux densities of galaxies in our sample (red circles). We also include T_d measurements and observed S_{850} flux densities of high- z SMGs by Chapman et al. (2005) (blue squares). Solid lines represent tracks in constant L_{IR} while the vertical dotted line indicates the confusion limit of current ground based submm surveys. It is evident that a significant fraction of our sample lies below the detection limit and would be missed the SCUBA-850 μm surveys, if we consider that the detection limit should be above the confusion.

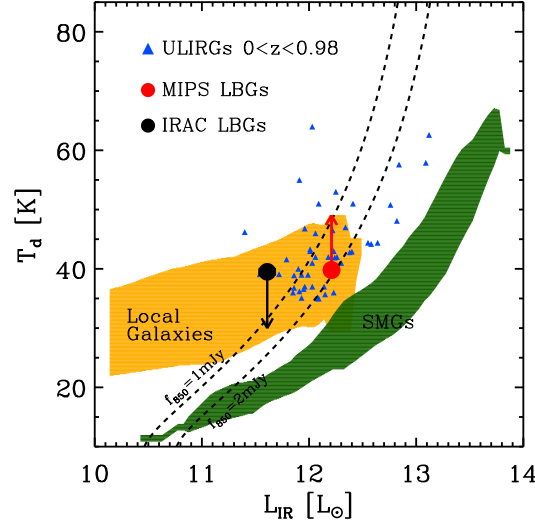


Figure 3. The $T_d - L_{\text{IR}}$ relation for MIPS and IRAC LBGs (red and black circles respectively). We note that these values correspond to 3σ upper and lower T_d limits for IRAC and MIPS LBGs. The green shaded region depicts the loci of high- z SMGs by Chapman et al. (2005), while the orange shaded area shows the 2σ envelope of the $L_{\text{IR}} - T_d$ relation for local IR galaxies in SDSS adopted from Hwang et al. (2010). Black dashed lines represent tracks of constant flux density at $850\mu\text{m}$ ($S_{850}=1\text{mJy}$ and $S_{850}=2\text{mJy}$) for galaxies at $z=3$. Objects at $z=3$ with higher S_{850} , lie on the right of the lines. Adopted from Magdis et al. (2010b)

galaxies in the class of ULIRGs (Magdis et al. 2010b,c). Considering the large L_{IR} and the substantial dust reddening of these LBGs it is somewhat surprising that there are only few examples of direct sub-millimeter detection for these galaxies. MIPS-LBGs are the most rapidly star-forming, most luminous, and dustiest galaxies among the high redshift UV-selected population, and therefore are the best candidates for having far-IR emission that could be detected in current sub-mm surveys. Based on the average SED of MIPS-LBGs as constructed by stacking at PACS, Aztec1.1mm and VLA1.4GHz maps (Magdis et al. 2010b), we predict that the flux density of the MIPS-LBGs emitted at $850\mu\text{m}$ is $S_{850}=1.1\text{--}1.5\text{mJy}$, just below the current confusion limit. It could therefore be suggested that MIPS-LBGs provide a link between SMGs and typical UV selected LBGs that are faint in the IR.

In Figure 3 we compare dust temperature versus infrared luminosity for the MIPS LBGs with that of the $z \sim 2$ SMGs by Chapman et al. (2005). We also plot, the 3σ envelope of the $L_{\text{IR}} - T_d$ relation for local infrared galaxies in SDSS (Hwang et al. 2010). It is evident that for the L_{IR} of the MIPS-LBGs, the bulk of SMGs are considerably colder, while MIPS-LBGs fall in the locus of the local ULIRGs and are within the scatter observed in local galaxies. Based on modified black body models, we also compute tracks of constant $850\mu\text{m}$ flux density for galaxies at $z=3$, close to the confusion/detection limit of current sub-mm surveys ($S_{850}=1\text{mJy}$ and $S_{850}=2\text{mJy}$). MIPS-LBGs lie in between the two tracks, indicating that a typical MIPS detected LBG emits at 1-2 mJy level at the sub-mm bands. This explains the small overlap between the LBGs and SMGs found in previous studies.

5. Conclusions

Based on *Herschel* observation of $z \sim 2$ and ~ 3 ULIRGs, as part of the PEP and HerMES projects, we explore the far-IR properties of these samples and find that :

- IRAC selected ULIRGs display a wide range of T_d , ranging from those that are as cold as high- z SMGs to objects as warm as OFRGs, while a significant fraction has intermediate T_d , bridging the two populations. This indicates that the mid-IR selection of high- z ULIRGs does not introduce a systematic bias in T_d .
- A significant fraction of $z \sim 2$ ULIRGs are missed from (sub)mm surveys, showing that the sub-mm technique introduces a bias towards the detection of colder ULIRG sources. On the other hand, *Herschel* data provide the means for a complete and unbiased selection of the census of ULIRGs at this redshift.
- The T_d dispersion of high- z ULIRGs is larger than that found in the local universe, indicating a wide range of mechanisms triggering the star formation activity at earlier epochs.
- Infrared luminous LBGs at $z \sim 3$, have warmer T_d than SMGs galaxies while they fall in the locus of the $L_{\text{IR}} - T_d$ relation of the local ULIRGs. This, along with estimates based on the average SED, explains the marginal detection of LBGs in current sub-mm surveys and suggests that these latter studies introduce a bias towards the detection of colder ULIRGs in the high- z universe, while missing high- z ULIRGs with warmer dust.

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References

- Chapman, S. C., et al., 2005, ApJ, 622, 772
 Chapman, S. C., et al., 2010, MNRAS, 409, 13
 Casey, C. M., et al., 2009, MNRAS, 399, 121
 Chary, R., Elbaz, D., 2001, ApJ, 556, 562
 Clements, D. L., Dunne, L., Eales, S., 2010, MNRAS, 403, 274
 Dale, D. A., Helou, G., 2002, ApJ, 576, 159
 Farrah, D., et al., 2003, MNRAS, 343, 585
 Fiolet et al., 2009, A&A, 508, 117
 Huang, J.-S. et al., 2009, ApJ, 700, 183
 Hwang, H.S., et al., 2010, MNRAS, 409, 75
 Hughes, D. H. et al., 1998, Nature, 394, 241
 Kovacs, A., et al., 2006, ApJ, 650, 592
 Le Floc'h, E. et al., 2005, ApJ, 632, 169
 Lonsdale, C. J. et al., 2009, ApJ, 692, 422
 Magdis G.E. et al., 2010a, MNRAS, 409, 22
 Magdis G.E. et al., 2010b, ApJ, 720, 185
 Magdis G.E. et al., 2010c, ApJ, 714, 1740
 Magnelli, B. et al. 2010, A&A, 518, 28
 Yang, M., et al., 2007, ApJ, 660, 1198